Dark Photons in electron-proton collisions
[arXiv:1909.02312]

Oliver Fischer
with Monica D’Onofrio and Simon Wang

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Model

- $U(1)_X$ extension of the Standard Model gauge group:
  \[ \mathcal{L} \supset \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\epsilon}{2} X_{\mu\nu} F^{\mu\nu} \]

- SM fermions $\Psi_f$ are uncharged under $U(1)_X$.

- Field redefinition to remove the gauge mixing term brings:
  \[ \mathcal{L} \supset - \sum_f \epsilon \, e \, q_f \, \overline{\Psi}_f \, \gamma_\mu \, \Psi_f \, A'_\mu, \]

- Dark photon acquires a mass, possibly via a Higgs mechanism.

- Explicitly: Abelian Higgs Model from C. Duhr.
Coupling to the electric charge defines its decay rate:

\[ \Gamma(\gamma' \to l^+ l^-) = \frac{1}{3} \alpha_{\text{QED}} m_{\gamma'} \epsilon^2 \sqrt{1 - \frac{4m_l^2}{m_{\gamma'}^2}} \left(1 + \frac{2m_l^2}{m_{\gamma'}^2}\right), \]

Its total decay rate can be obtained in this way:

\[ \Gamma_{\text{total}}(\gamma') = \frac{\Gamma(\gamma' \to e^- e^+)}{\text{BR}(\gamma' \to e^- e^+)}. \]
Dark photon production

- Process $e^- p \rightarrow e^- X \gamma'$, $X$ final state hadrons
- Initial/final state radiation off the electron dominates.
  $\Rightarrow$ Process not very sensitive to proton beam parameters.
- Like QED, cross section diverges with $p_T \rightarrow 0$.
- We consider deep inelastic scattering regime: $Q^2 \gg m_p$. 
Signature

- Final state $e^- X \gamma'$ with displaced decays $\gamma' \rightarrow f^+ f^-$
- $f^{\pm}$ are charged SM particles (read “electrons”).
- All final states $|\eta| < 4.7$.
- For small momentum transfer scattering angles of the $e^-$ and $X$ are small compared to the respective beams.
- Primary vertex (PV) inferred from the tracks of $X$ and $e^-$. 
- Impact parameter resolution from CDR for vertex precision: $\mathcal{O}(10) \mu m$ at large scattering angles to $200 \mu m$ for $\theta \sim 1^\circ$.

Displaced dark photon decays

The expected number of dark photon decays with a given displacement can be quantified with:

\[ N_{dv} = \sigma_{e^- p \to e^- X \gamma'} L \times \int D(\vartheta, \gamma) P_{dv} d\vartheta d\gamma. \]

- Luminosity: \( L_{\text{LHeC}} = 1/\text{ab}, \ L_{\text{FCC-he}} = 3/\text{ab} \)
- The 2d distribution \( D \) from WHIZARD simulation.
- The probability of decay

\[ P_{dv} = \text{Exp} \left( \frac{-x_{\text{min}}}{\Delta x_{\text{lab}}} \right) - \text{Exp} \left( \frac{-x_{\text{max}}}{\Delta x_{\text{lab}}} \right). \]

- We consider displacements bigger than 200\( \mu \text{m} \).
Expected signal events

- **LHeC, Pt (X)=5 GeV**
  - $N=1$
  - $N=10$
  - $N=100$

- **FCC-he, Pt (X)=5 GeV**
  - $N=1$
  - $N=10$
  - $N=100$

- **LHeC, Pt (X)=10 GeV**
  - $N=1$
  - $N=10$
  - $N=100$

- **FCC-he, Pt (X)=10 GeV**
  - $N=1$
  - $N=10$
  - $N=100$
First look at possible backgrounds

- Most important for dark photon masses below muon production threshold.
- Low-energy photons from $e^- p \rightarrow e^- X \gamma$, interacting with the detector material or the beam pipe.  
  $\Rightarrow$ Secondary vertex coincides with known material.
- Long-lived mesons ($K_S$, $K_L$, and $\Lambda$).
  - lifetimes $\mathcal{O}(10)$ cm and longer,
  - expected to be aligned with the proton beam,
  - primary decay channels very different and masses are well known.
- Others (e.g. Cosmics or other machine related backgrounds).

- We consider four scenarios:
  - $N_{bgk} = 1, 100$ with flat distribution.
  - signal efficiency $= 20\%, 100\%$.
  - Everything for 90\% confidence level.
Projected sensitivity of dark photon searches

Present exclusion,
- lower left corner: E141, E774, Orsay, and NuCal;
- upper limit: NA48 and BaBar.

LHCb searches for long-lived particles.

Preliminary results were created for the European strategy.
From the European Strategy
Detour: exotic Higgs decays to scalar LLPs

- First look at the parton level, input for ESPP update.
- Assumption: background free and 100% signal efficiency.
- Work in progress with J. Zurita.
Conclusions

- Dark photons are part of many BSM sectors.
- They are searched for by many experiments.
- LHC searches are limited by di-muon threshold.
- Electron-proton colliders surprisingly good probe for “light” dark photons.
- Signature relies on lifetimes (around mm), tracking resolution, absence of pile up and low number of backgrounds.
- There are additional production channels worth studying.